JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, G01021, doi:10.1029/2005JG000107, 2007

Changes in soil organic carbon induced by tillage and water erosion on a steep cultivated hillslope in the Chinese Loess Plateau from 1898–1954 and 1954–1998

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Received 29 September 2005; revised 26 September 2006; accepted 27 October 2006; published 1 March 2007.

[1] The fate of soil organic carbon (SOC) transported and redistributed by erosion over steep agricultural landscapes is uncertain. The effect of topography, slope, and slope position on SOC redistribution must be considered. Our objectives were to (1) determine the spatial patterns of both tillage and water erosion-induced SOC redistribution, (2) evaluate the compensating effects of tillage-induced soil redistribution on SOC loss due to water erosion, and (3) quantify changes of SOC storage between 1898–1954 and 1954–1998 periods. To meet these objectives, we conducted field sampling and investigated a cultivated hillslope in the Fangzhuang gully of Xigoumao catchment in Chinese Loess Plateau. Soil organic carbon redistribution was calculated by multiplying SOC concentration by total soil redistribution (TSR) including both tillage and water-induced soil redistribution derived from ^{137}Cs and ^{210}Pb$_{ex}$ inventories and from the tillage erosion prediction (TEP) model. Our results showed that the hillslope soil had an 89% decrease of ^{137}Cs inventories for the last 45 years and a 55% decrease of ^{210}Pb$_{ex}$ inventories for the last 100 years. The major losses of SOC over the entire hillslope are attributed to severe water erosion. Significant increase of SOC at the lower field boundaries on the summit and upper backslope resulted from tillage-induced soil redistribution by moldboard plowing. Tillage-induced soil redistribution increased SOC and compensated for 8–14% of the SOC losses due to water erosion during 1898–1998, but the total soil erosion reduced SOC pool over the steep cultivated hillslope of the Loess Plateau. During the period 1898–1954, the net SOC loss from the entire hillslope was 1.65 t C ha^{-1} (0.03 t C ha^{-1} yr^{-1}). Within the period 1954–1998, the net SOC loss was 10.65 t C ha^{-1} (0.24 t C ha^{-1} yr^{-1}). The positive relationship between SOC with ^{137}Cs and ^{210}Pb$_{ex}$ confirmed the utility of fallout radionuclides as a promising method for tracing tillage and water erosion impacts on SOC dynamics covering a timescale of 45 to 100 years.

Citation: Li, Y., Q. W. Zhang, D. C. Reicosky, M. J. Lindstrom, L. Y. Bai, and L. Li (2007), Changes in soil organic carbon induced by tillage and water erosion on a steep cultivated hillslope in the Chinese Loess Plateau from 1898–1954 and 1954–1998, *J. Geophys. Res.*, *112*, G01021, doi:10.1029/2005JG000107.

1. Introduction

[2] Carbon (C) stored in soils represents globally significant carbon pool, which has the potential to influence global climate [*Lal*, 2003; *Polyakov and Lal*, 2004]. The fate of SOC redistribution caused by soil erosion is a controversial subject. Accelerated soil erosion involves preferential removal of soil organic carbon (SOC) that is concentrated in the surface horizon. Many studies document that soil erosion is one of the most important driving forces for the terrestrial surface C cycle [*Stallard*, 1998; *Gregorich et al.*, 1998; *Harden et al.*, 1999; *Lal*, 2003; *Lal et al.*, 2004a, 2004b; *Reicosky et al.*, 2005; *Van Oost et al.*, 2004, 2005; *Yoo et al.*, 2005a]. Some studies proposed that soil erosion depletes the SOC pool, and losses of SOC due to erosion on sloping land may be several times greater than the losses via mineralization alone [*Webber*, 1964; *Lal*, 2003]. Consequently, the SOC pool is much lower in eroded soils than in noneroded soils [*De Jong and Kachanoski*, 1988; *Lal*, 2003; *Oskarsson et al.*, 2004]. In contrast, studies by *Stallard* [1998], *Harden et al.* [1999] and *Ritchie and McCarty* [2003] argued that significant amounts of carbon might be stored in sediments in man-made reservoirs and other depositional sites. *Stallard* [1998] proposed that SOC buried with sediments is physically protected and that carbon depleted in the eroded soil is replaced through biomass production. Thus they argued that the erosion-sedimentation process leads to a net SOC sequestration of 0.6–1.5 Gt C yr^{-1} globally [*Stallard*, 1998; *Smith et al.*,

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0148-0227/07/2005JG000107$09.00

2001; *Renwick et al.*, 2004]. Although the question of the SOC fate during transition from sediment source to sediment sinks has been raised in the literature [*Lal*, 1995], field data are scarce to validate this question [*Polyakov and Lal*, 2004, *Yoo et al.*, 2005a]. There is an urgent need to obtain reliable quantitative data on SOC patterns in relation to soil erosion for determining whether accelerated soil erosion is a source or sink of atmospheric CO_2.

[3] The quest for alternative techniques for assessing the fate of eroded SOC to complement classical methods has led to the use of radionuclides as tracers to obtain quantitative estimates of eroded SOC redistribution over agricultural landscapes. Environmental radionuclides, in particular ^{137}Cs, are an effective way for studying soil redistribution within the agricultural landscape [*Wallbrink and Murray*, 1993; *Zapata*, 2003; *Li et al.*, 2003]. Cesium-137 is an artificial radionuclide (half-life 30.2 years) produced as a consequence of atmospheric testing of nuclear weapons, which commenced in the mid-1950s. The ^{137}Cs is strongly fixed by clay minerals [*Ritchie and McHenry*, 1990]. *Mabit and Bernard* [1998] found a significant correlation between the ^{137}Cs and soil organic matter contents after estimating the erosion risks in a small agricultural watershed in northeastern France. *Ritchie and McCarty* [2003] proposed that both ^{137}Cs and SOC are moving along similar physical pathways, but there is a lack of direct field evidence to support this proposal.

[4] Another fallout radionuclide for estimation of sedimentation rate is ^{210}Pb [*Walling et al.*, 2003]. The ^{210}Pb produced in the soil is termed 'supported,' while the additional ^{210}Pb from radionuclide fallout is termed unsupported or excess ^{210}Pb ($^{210}Pb_{ex}$). Lead-210 with a half-life of 22.3 years is formed in the atmosphere by the normal decay of ^{222}Rn, which diffuses as a gas from the soil. While the measurements involved in ^{210}Pb and ^{137}Cs are similar, the deposition of atmospheric ^{210}Pb is relatively constant over time, but is spatially variable [*Cannizzaro et al.*, 1999] In our previous studies [*Li et al.*, 2003, 2006], we estimated SOC redistribution affected by intensive tillage and linked SOC to profile variations of ^{137}Cs and $^{210}Pb_{ex}$ inventories.

[5] In most environments, bomb-derived fallout ^{137}Cs and unsupported ^{210}Pb in the soil, just like SOC, are strongly adsorbed to soil particles in the ground surface. Subsequently, the soil particles are redistributed primarily through physical processes such as water- and wind-induced soil erosion and tillage-induced erosion. The main benefit of using ^{137}Cs and $^{210}Pb_{ex}$ techniques to quantify the soil redistribution-SOC relationship is that these elements provide retrospective information on medium-term (45-year span) and long-term (100∼150 year span) redistribution patterns of eroded SOC within the hillslope landscapes. These assume a strong and consistent association between ^{137}Cs and $^{210}Pb_{ex}$ and SOC [*Li et al.*, 2006]. Once the strong association was established, ^{137}Cs and $^{210}Pb_{ex}$ can be used to predict the fate of the eroded SOC and further assess soil redistribution effects on C dynamics and emission of carbon dioxide (CO_2) into the atmosphere. Here our overall objective is to assess the effectiveness of using ^{137}Cs and $^{210}Pb_{ex}$ to measure change in SOC induced by water erosion integrated with tillage erosion by moldboard plowing over a cultivated hillslope on the Chinese Loess Plateau.

[6] The hilly-gully region of the Chinese Loess Plateau probably has the highest rate of soil erosion in the world [*Fu et al.*, 2000]. According to *Chen and Luck* [1989], the average and maximum rates of soil loss are 150 and 390 Mg ha^{-1} yr^{-1}, respectively, which are equivalent to a surface lowering of 1.2 and 3.1 cm yr^{-1}. The serious water erosion and tillage erosion on the Chinese Loess Plateau have resulted in severe soil and subsequently SOC redistribution. Therefore the patterns of soil redistribution need to be quantified to better understand the SOC dynamics. Review of previous studies on C redistribution and loss by erosion show three main ways that the physical processes of erosion and deposition impact soil C distribution [*Gregorich et al.*, 1998; *Yoo et al.*, 2005b]. First, soil erosion drastically alters the biological process of C mineralization in the soil landscapes. Second, soil C is redistributed within hillslopes or further transported to lower depositional areas. Third, soil erosion and deposition can affect soil C distribution by altering the thickness of soils that serve as the size of soil container storing carbon. Owing to the gentle slopes of the target sites, some studies attributed SOC losses to mineralization processes. However, in hilly-gully regions of Chinese Loess Plateau with slopes ranging from 5% to 137%, it is reasonable to expect that tillage-induced SOC loss by moldboard plowing occurs across the eroded landscapes, particularly in the upper and mid slope positions, with long-term and intensive tillage practices.

[7] The specific objectives of this research were (1) to determine the spatial patterns of erosion-induced SOC redistribution, (2) to evaluate the compensating effects of tillage-induced soil redistribution on SOC loss due to water erosion, and (3) to quantify changes of SOC storage (mass per area) between 1898–1954 and 1954–1998 periods, since 1954 is the year that bomb testing began and thus fallout ^{137}Cs can be used for the time period after the year. To meet these objectives, a small watershed on Chinese Loess Plateau was chosen for assessing spatial distributions of SOC and fallout ^{137}Cs and $^{210}Pb_{ex}$ inventories on the cultivated hillslope.

2. Materials and Methods

2.1. Study Area

[8] The field sampling was conducted in the Fangzhuang gully of Xigoumao catchment (36°49.5′N, 109°32′E), located near Yan'an city on the Chinese Loess Plateau in November of 1998. Fuangzhuang gully has a semiarid continental monsoon climate. Long-term mean annual temperature is 9.2, and precipitation is 500 mm with a 70% of annual rainfall distribution from July to September. The soils formed from loess parent material with uniform soil texture in the profile (22% clay, 51% silt, and 27% sand), and classified as Calciustepts according to the U.S. taxonomic classification system [*Soil Survey Staff*, 1999]. Water erosion and tillage erosion by moldboard plowing are particularly problematic because of the extremely high erodibility of the Chinese Loess Plateau soils [*Li*, 1995]. Soil organic carbon contents are low owing to (1) intensive tillage and erosion, (2) the human harvest of the vegetation, and (3) the steepness of the hillslopes. Soil organic carbon concentrations in the Loess soil are commonly between 0.1 and 2.4%, but less than 1% in most cases [*Zhu*, 1989]. Pearl millet (*Pennisetum glaucum* (*L.*) *R. Br*) and soybean (*Glycine max* (*L.*) *Merr.*) are the major crops in the rotation

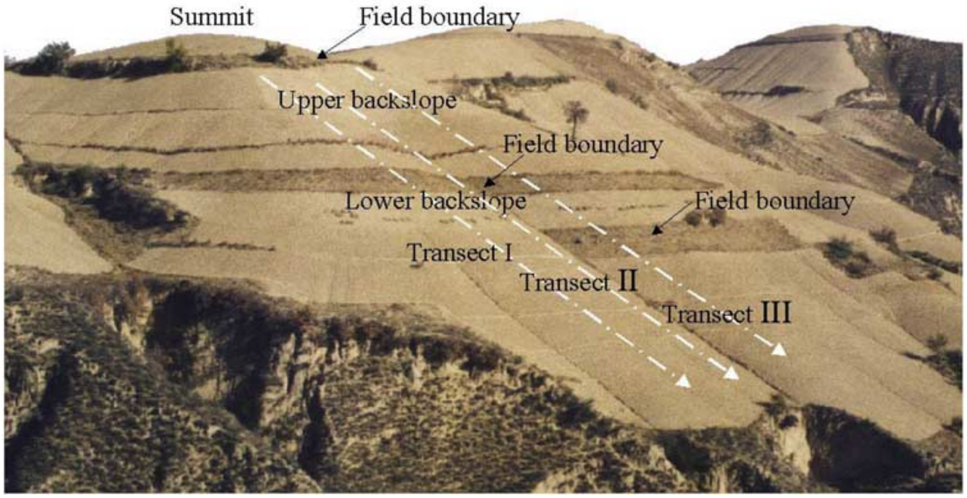

Figure 1. Sampling transects for tracing SOC, ^{137}Cs, and ^{210}Pb$_{ex}$ changes on a steep cultivated hillslope in the Chinese Loess Plateau.

with potato (*Solanum tuberosum L.*) and corn (*Zea mays L.*) growing in the study area. The natural grasses in the catchment are K.R. (King Ranch) Bluestem (*Bothriochloa ischaemum*), Red oat grass (*Themeda triandra var. Japonica*), and Hair-tail Cotton-grass (*Eriophorum Linn*).

2.2. Soil Sampling

[9] The spatial patterns of the eroded SOC and ^{137}Cs and ^{210}Pb$_{ex}$ inventories were documented from soil cores taken on three downward slope transects on the cultivated hillslope (Figures 1 and 2), using a 6.74-cm-diameter hand-operated core sampler. Reference sites for determining the ^{137}Cs and ^{210}Pb$_{ex}$ inventories were established on uncultivated grassland at the hilltop within the study catchment. Soil cores were taken to a depth of 40 cm to ensure that the core had penetrated to the full depth of the ^{137}Cs and ^{210}Pb$_{ex}$ profile. Three soil core samples were taken at each site and composed to one sample. Soil cores were also analyzed for bulk densities (g cm^{-3}), calculated from the volume of soil cores and oven-dried soil mass. There was about 5 m horizontal distance between two adjacent sloping transects. For each downward transect, soil cores were collected at 10-m intervals on the summit and upper backslope and 15–20 m on the lower backslope. The field boundary existed at the lower position of the summit and upper backslope (Figure 1). An electronic theodolite was used for detailed topographic surveys of the coring locations. The elevation of the hillslope was 80.3 m, and the hillslope length was about 263 m.

2.3. Laboratory Analysis

[10] Soil samples were air-dried, weighed, and divided into two parts, one passing through a 0.15-mm sieve for the measurement of SOC concentration and the other passing

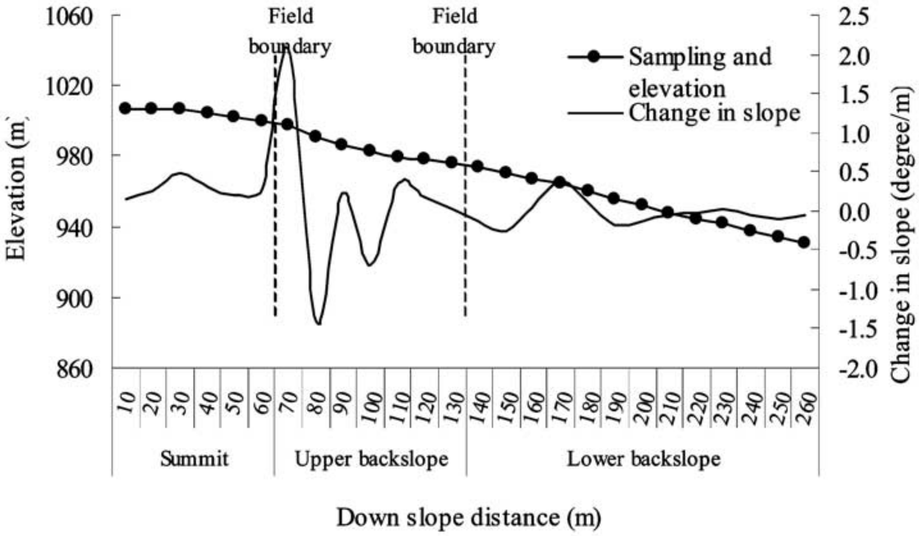

Figure 2. Profile of a transect on the steep cultivated hillslope showing changes in slope gradients and sampling points.

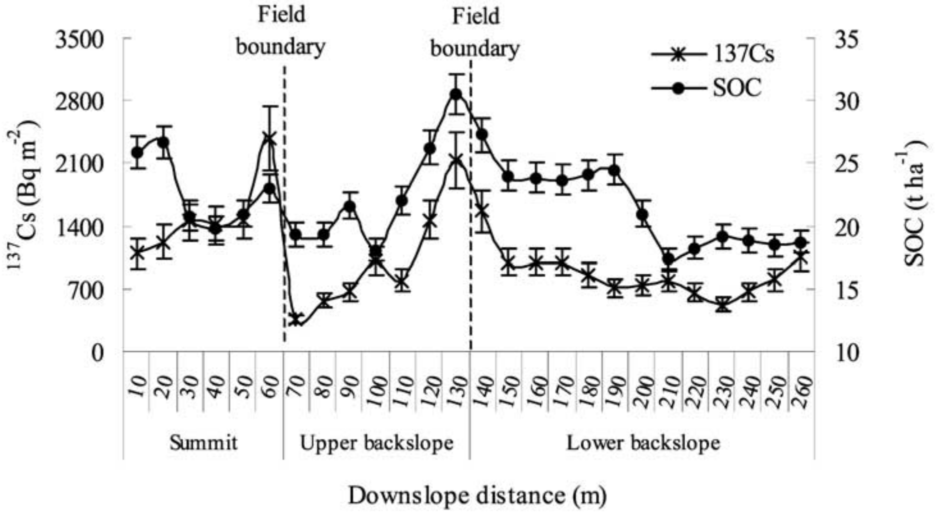

Figure 3. Downslope variations in ^{137}Cs inventory and SOC of a transect on the steep cultivated hillslope.

through a 2-mm sieve for the measurements of ^{137}Cs and ^{210}Pb$_{ex}$ activities. Soil samples for measuring ^{210}Pb were sealed in containers and stored for 28 days to ensure equilibrium between ^{226}Ra and its daughter ^{222}Rn (half-life 3.8 days). The amounts of ^{210}Pb$_{ex}$ of the samples were calculated by subtracting ^{226}Ra-supported ^{210}Pb concentration from the total ^{210}Pb concentrations. Measurements of ^{137}Cs and ^{210}Pb$_{ex}$ activities were conducted using a hyperpure coaxial Ge detector coupled to a multichannel analyzer [*Li et al.*, 2003]. Cesium-137 activity was detected at 662 keV peak while total ^{210}Pb concentration was determined at 46.5 keV, and the ^{226}Ra-supported ^{210}Pb was obtained at 609.3 keV using counting time over 80,000 s, which provided an analytical precision of ±5% for ^{137}Cs and ±8% for ^{210}Pb [*Li et al.*, 2006].

[11] Soil organic matter (SOM) was measured by the combustion method [*Nelson and Sommers*, 1982] as SOM percentage and converted to SOC percentage by multiplying by a factor of 0.58. The SOC amount over the cultivated hillslope was obtained by multiplying the SOC percentage by soil bulk density (g cm^{-3}) and soil depth (cm) of each sampled soil and expressed in mass per unit area (t C ha^{-1}).

2.4. Data Analysis

[12] Using ^{137}Cs and ^{210}Pb$_{ex}$ to understand soil redistribution involves the comparison of the measured inventories (total activity in the soil profile per unit area) at all sample sites with an estimate of the total atmospheric input obtained from a "reference site." By the comparison, one can determine whether erosion (less ^{137}Cs and ^{210}Pb$_{ex}$ present than at the reference site) or deposition (more ^{137}Cs and ^{210}Pb$_{ex}$ than at the reference site) has occurred. At each sampling point, TSR, total soil redistribution due to combined action of tillage and water erosion, was determined for the periods of 1954–1998 and 1898–1998 using ^{137}Cs and ^{210}Pb$_{ex}$, respectively, following the mass balance model developed by *Walling et al.* [1997, 2003]. Tillage-induced soil redistribution rates were estimated using the Tillage Erosion Prediction Model (TEP) from topographic data collected in the field [*Lindstrom et al.*, 2000; *Li and Lindstrom*, 2001]. An appropriate *k*-value of 250 kg yr^{-1} m^{-1}, representing a mean annual tillage transport coefficient per unit slope gradient for animal-drawn tillage in the Chinese Loess Plateau [*Li and Lindstrom*, 2001], was used for simulation of tillage-induced soil redistribution from TEP. TSR-induced SOC redistribution was calculated by multiplying SOC concentration (%) by TSR (t ha^{-1} yr^{-1}). Tillage-induced SOC redistribution was calculated by multiplying SOC concentration by tillage-induced soil redistribution rates. Water erosion–induced SOC loss was calculated by subtracting SOC loss due to tillage-induced soil redistribution from that due to TSR.

[13] One-way analysis of variance (ANOVA) at $\alpha = 0.05$ probability was conducted to test the significance in the spatial patterns of SOC, ^{137}Cs and ^{210}Pb$_{ex}$ over the hillslope. The coefficients of variation of SOC, ^{137}Cs and ^{210}Pb$_{ex}$ inventories were calculated as CV = (standard deviation/mean) × 100. Regression modeling techniques were used to develop relationships between SOC with ^{137}Cs and ^{210}Pb$_{ex}$ on the hillslope. All statistical analyses were performed using Statistical Analysis System (SAS) General Linear Model procedures [*SAS Institute*, 1990].

3. Results

3.1. Spatial Patterns of SOC and ^{137}Cs and ^{210}Pb$_{ex}$ Inventories

[14] The ^{137}Cs varied significantly among different slope positions (Figure 3). The amounts of ^{137}Cs increased at the lower field boundaries of summit and upper backslope while significant decreases in total amount of ^{137}Cs were shown over the entire cultivated hillslope. Cesium-137 amounts decreased in the following order: summit > upper backslope > lower backslope (Table 1). Reference values of ^{137}Cs and ^{210}Pb$_{ex}$ inventories calculated were 1761 ± 72 Bq m^{-2} and 6123 ± 969 Bq m^{-2}, respectively. As compared with ^{137}Cs amounts at the reference site, ^{137}Cs inventory losses were 83%, 89% and 95% at the summit, upper and lower back-

Table 1. Statistical Values for SOC, ^{137}Cs, and ^{210}Pb$_{ex}$ Inventories in the Different Slope Positions[a]

	SOC, t C ha^{-1}			^{137}Cs, Bq m^{-2}			^{210}Pb$_{ex}$, Bq m^{-2}		
Statistics	Summit	Upper Backslope	Lower Backslope	Summit	Upper Backslope	Lower Backslope	Summit	Upper Backslope	Lower Backslope
Mean	22.82a	21.79a	20.87a	1502.52b	922.42c	875.61c	7755.98d	5540.26e	5176.67f
StDev	3.18	2.86	5.06	544.09	361.12	384.251	1872.31	1883.35	2103.21
CV, %	14.18	14.67	21.82	33.22	45.65	41.64	30.34	32.30	27.91
n	17	16	16	17	15	19	17	13	16

[a] Figures followed by the same letters within a row are not significantly different at $\alpha = 0.05$ probability based on one-way analysis of variance (ANOVA).

slopes, respectively, whereas ^{137}Cs inventory gains were 17% for the lower field boundary of the summit, and 11% for the lower field boundary of upper backslope (Figure 3). During 1954–1998, tillage and water erosion resulted in an 89% decrease of ^{137}Cs for the entire hillslope.

[15] Like ^{137}Cs, the amounts of ^{210}Pb$_{ex}$ had a spatial pattern related to slope positions (Figure 4). Inventories of ^{210}Pb$_{ex}$ were significantly higher on the hilltop and the lower field boundaries of summit and upper backslope, but the total amount of the ^{210}Pb$_{ex}$ showed a decreasing trend over the entire hillslope. By comparing with ^{210}Pb$_{ex}$ inventories at the reference site, ^{210}Pb$_{ex}$ losses were 22%, 72%, 71% on the summit, upper and lower backslope, respectively, whereas ^{210}Pb$_{ex}$ gains were 78% for the lower field boundaries of the summit and 28% and 29% for the lower field boundaries of upper and lower backslopes. Tillage and water erosion has resulted in a 55% loss of total ^{210}Pb$_{ex}$ inventories for the entire cultivated hillslope over the last 100 years. Table 1 showed ^{210}Pb$_{ex}$ inventory for the hillslope decreased in the following order: summit > upper backslope > lower backslope.

[16] SOC storage shows spatial distributions that are nearly identical to those of ^{137}Cs and ^{210}Pb$_{ex}$ inventories: They all show increased values at the lower positions within summit and upper backslope (Figures 3 and 4). The SOC storage at 0–40 cm depth for the hillslope decreased, although not significantly, in the following order: summit > upper backslope > lower backslope (Table 1).

3.2. Soil Organic Carbon Displaced by Tillage and Water Erosion

[17] Within the period 1954–1998, net SOC loss due to water erosion from the entire hillslope was 11.22 t C ha^{-1} (0.249 t C ha^{-1} yr^{-1}), showing a significant decrease in SOC storage within the upper and lower backslopes, but a slight decrease within the summit (Figure 5). Over the last 45 years, the mean annual rate of SOC loss was calculated from different slope positions to 0.004, 0.057, and 0.196 t C ha^{-1} yr^{-1} on the summit, the upper and lower backslopes, respectively. In contrast, for the period 1954–1998, tillage-induced soil redistribution noticeably increased SOC storage at the rate of 0.022 t C ha^{-1} yr^{-1} on the summit and 0.014 t C ha^{-1} yr^{-1} on the upper backslope, as compared with a decrease at the rate of 0.016 t C ha^{-1} yr^{-1} in the lower backslope. A net SOC gain by tillage-induced soil redistribution for the entire hillslope was 0.90 t C ha^{-1}, showing a mean rate of 0.020 t C ha^{-1} yr^{-1}, which compensated for 8% of the SOC loss due to water erosion. A schematic (Figure 6) shows the change in SOC induced by tillage and water erosion for different hillslope positions over the last 45 years.

[18] Similarly, in the period 1898–1954, water erosion significantly decreased SOC along the down hillslope at the

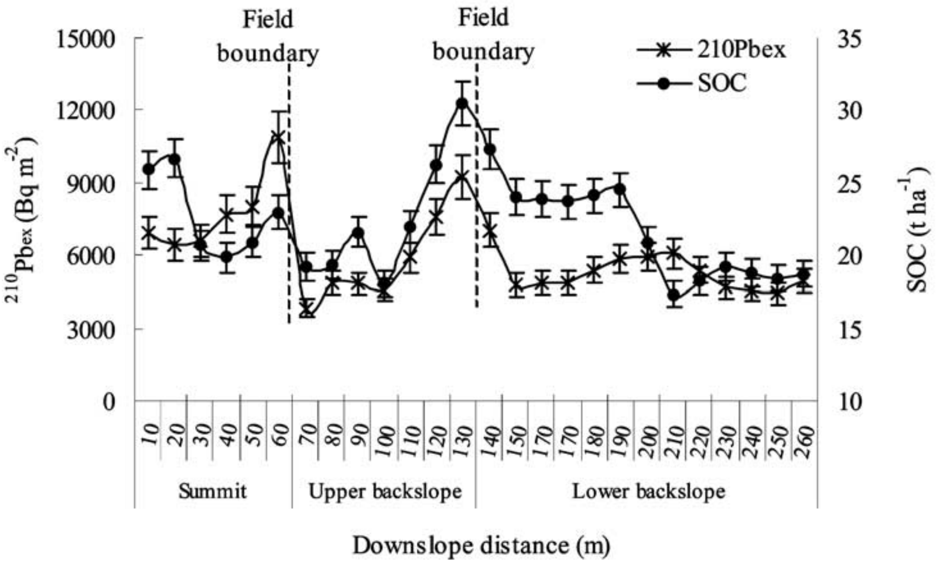

Figure 4. Downslope variations in ^{210}Pb$_{ex}$ inventory and SOC of a transect on the steep cultivated hillslope.

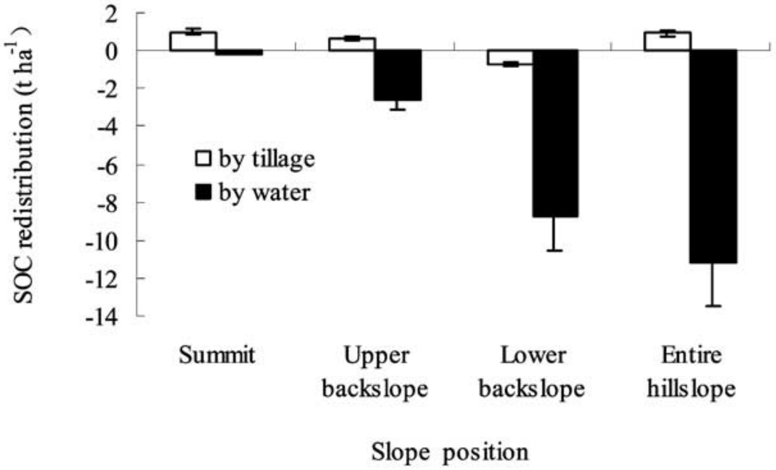

Figure 5. Change in SOC redistributed by tillage and water erosion for different slope positions during the period 1954–1998.

rate of 0.007 t C ha^{-1} yr^{-1} on the summit, 0.020 t C ha^{-1} yr^{-1} on the upper backslope, and 0.116 t C ha^{-1} yr^{-1} on the lower backslope (Figure 7). The net SOC loss due to water erosion was calculated from the entire hillslope to 7.87 t C ha^{-1} (0.143 t C ha^{-1} yr^{-1}). In contrast, the net SOC gain by tillage-induced soil redistribution was 1.11 t C ha^{-1}, which compensated for 14% of the SOC loss due to water erosion.

3.3. Changes of SOC Stock by TSR Between 1898–1954 and 1954–1998 Periods

[19] Within the period 1954–1998, TSR slightly increased SOC stock rates on the summit with a SOC gain of 0.84 t C ha^{-1}, but significantly decreased SOC stock on the upper and lower backslope with SOC losses of 1.96 and 9.53 t C ha^{-1}, respectively (Figure 8). The TSR-induced SOC loss from the entire study hillslope was calculated to 10.65 t C ha^{-1}(0.237 t C ha^{-1} yr^{-1}).

[20] Similarly, in the period 1898–1954, the TSR increased SOC stock rates on the summit and the upper backslope with SOC gains of 0.69 and 1.38 t C ha^{-1}, respectively. In contrast, the TSR decreased SOC stock on the lower backslope with a SOC loss of 3.72 t C ha^{-1}. The TSR-induced SOC loss for the entire hillslope was calculated to 1.65 t C ha^{-1} (0.030 t C ha^{-1}yr^{-1}).

[21] By comparison, there was a SOC gain of 0.15 t C ha^{-1} during 1954–1998 on the summit and 3.34 and 5.81 t C ha^{-1} of SOC was lost on the upper and lower backslopes, respectively. To estimate the significance of TSR driven SOC redistribution in the changing SOC storage, we divided the differences in the SOC stock rates between two periods (1954–1998 and 1898–1954) by SOC stock rates within the period 1898–1954, in unit of % [*Bellamy et al.*, 2005]. The result is that the changing ratios of SOC stock rates

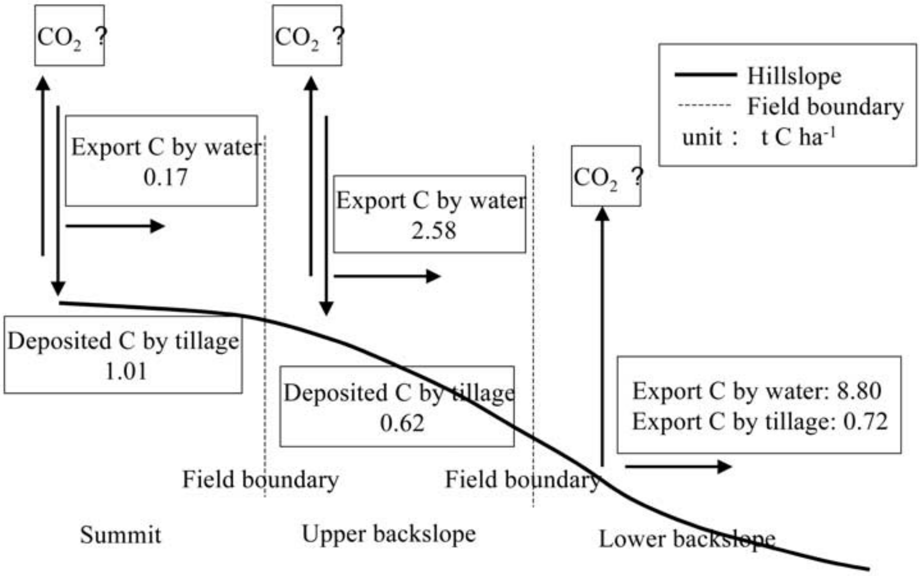

Figure 6. A schematic showing the change in SOC redistributed by tillage and water erosion for different hillslope positions during the period 1954–1998.

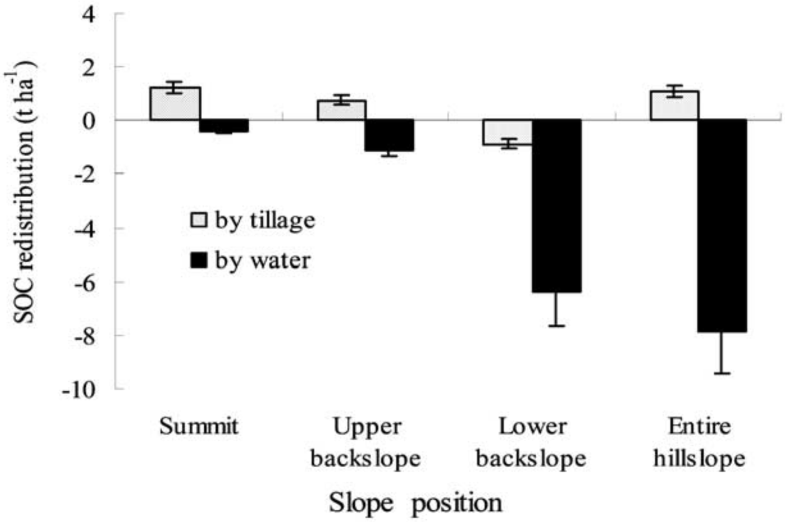

Figure 7. Change in SOC redistributed by tillage and water erosion for different slope positions during the period 1898–1998.

between the two periods were 0.49, −2.74, −2.13, −6.89% on the summit, the upper and backslopes, and the entire hillslope, respectively. The negative ratios indicated that more SOC was lost owing to TSR during the period 1954–1998 than during 1898–1954 on the upper and lower backslopes and the entire cultivated hillslope. Corresponding total loss in SOC was 1.65 t C ha^{-1} during the period 1898–1954 compared with 10.65 t C ha^{-1} during 1954–1998 for the steep cultivated landscapes. These data have been used to estimate the total losses of TSR-induced SOC on the entire cultivated Loess Plateau of 1.65 M ha [*Liu*, 1985] to be 0.18 Gt C in the last 45 years and 0.21 Gt C over the last 100 years.

3.4. Implication of ^{137}Cs and ^{210}Pb$_{ex}$ for Assessing the Fate of Eroded SOC

[22] The results revealed a significant relationship between SOC and TSR, as evidenced from ^{137}Cs and ^{210}Pb$_{ex}$ data. The low SOC of eroded locations (less ^{137}Cs and ^{210}Pb$_{ex}$ inventories than at the reference sites) and the high SOC of deposition locations (more ^{137}Cs and ^{210}Pb$_{ex}$ inventories than at the reference sites) implied that total amounts of SOC, the accumulative results of changes in redistributed and original SOC and in situ plant productivity, are in agreement with TSR covering a timescale of 45 to 100 years. Regression analysis indicated a positive correlation between SOC amounts with ^{137}Cs and ^{210}Pb$_{ex}$ inventories for the hillslope landscape (Figures 9a and 9b). The SOC storage was significantly linearly correlated with ^{137}Cs and ^{210}Pb$_{ex}$ inventories over the hillslope with R^2 of 0.35 and 0.36 ($P < 0.001$), respectively. It is, however, important to recognize that estimates of SOC redistribution associated with TSR obtained from ^{137}Cs and ^{210}Pb$_{ex}$ measurements represent medium (45 years) and long-term (100 years) average rates.

4. Discussion

[23] China's Loess Plateau is complex with very steep slope. Narrow summit positions and steep linear backslopes

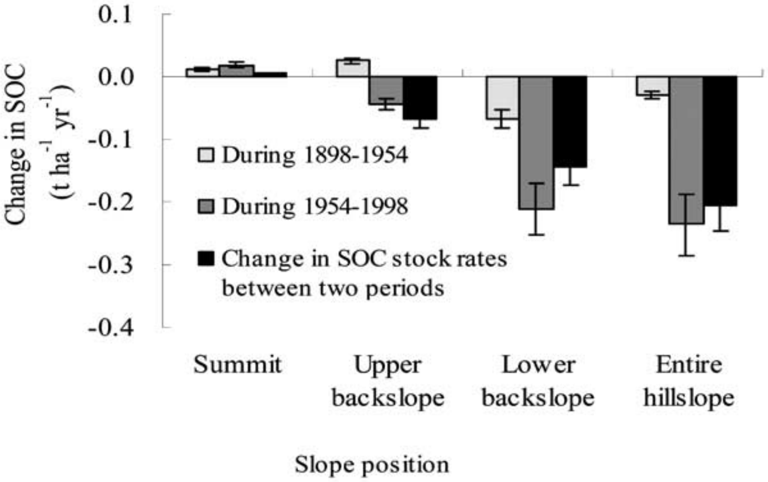

Figure 8. Change in SOC stock rates by TSR between 1898–1954 and 1954–1998 periods.

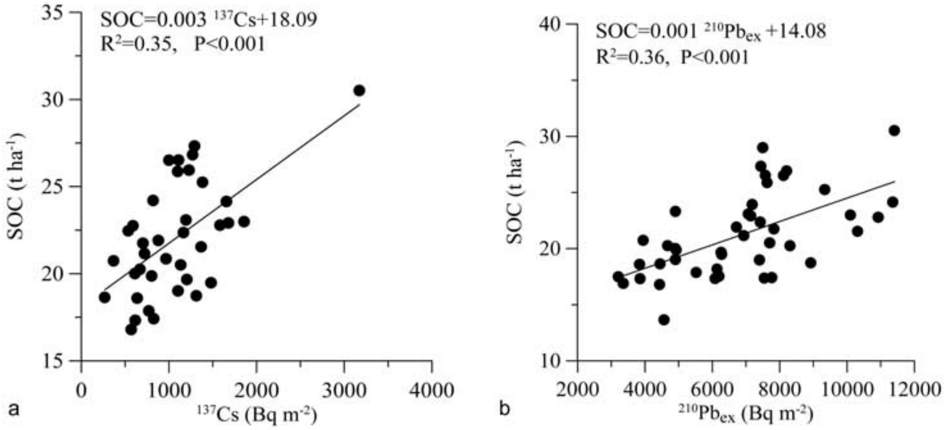

Figure 9. Correlation between SOC amounts with (a) ^{137}Cs and (b) ^{210}Pb$_{ex}$ inventories.

characterize the Loess Plateau (Figures 1 and 2). Soil redistribution due to tillage and water erosion, depending on the configuration of the landscape, can concentrate SOC in depositional areas. The direction of overland flow and soil translocation due to tillage are determined by the slope and curvature of the land surface. The impacts of topography on SOC dynamics were assessed by the changes in adjacent slope gradients, determined as the difference between the slope segment immediately above and below the sampling point [*Li and Lindstrom*, 2001]. The positive changes in slope gradients at the lower field boundary of the summit and the lower position of upper backslope (Figure 2) signifies concave slopes with higher SOC content. The slope gradient at the summit changed from 4.8% to 26.2% with an average downslope gradient of 17.7%. Although the backslope area was steeper with gradients ranging from 2% to 103%, SOC concentration was higher on the concave slope at the field boundary of the upper backslope. The intense tillage by moldboard plowing coupled with high slope gradient led to more water and tillage erosion and subsequently high deposition at the lower field boundary. The magnitude of soil loss or gain over the landscape was dependent on the degree of slope curvature rather than slope steepness [*Li and Lindstrom*, 2001]. Soil organic carbon storage showed no significant relationship with slope gradient in this study. More SOC was stored on concave slopes of the field boundary, reflected by much darker soil color (Figure 1).

[24] Significant increases in SOC at the field boundaries on concave parts of the summit and upper backslope were the result of soil accumulation due to multiple tillage operations whereas the overall losses of SOC on the entire hillslope are attributed to water erosion. On the Chinese Loess Plateau, heavy rainfall during summer and early autumn causes severe water erosion. Water erosion was more visible than tillage-induced soil redistribution of SOC. However, water erosion alone cannot explain the higher inventories of ^{137}Cs and ^{210}Pb$_{ex}$ at the lower field boundaries of the summit and upper backslope. There has been a long history of tillage in the Chinese Loess Plateau; however, tillage-induced soil redistribution has not been considered where water erosion is considered extremely serious. Traditionally, farmers plow their fields with an animal-drawn moldboard from the lower boundary of the hillslope along the contour and gradually move upslope, turning the soil downslope. As the tillage occurs, SOC is preferentially removed downslope with the surface soil [*Li et al.*, 2004]. Tillage-induced soil redistribution resulted in a SOC loss in the upper slope and temporary accumulation in the lower position of the field boundary. The data from TEP model yielded a mean tillage erosion rate of 11.7 t C ha^{-1} yr^{-1}, and a mean deposition rate of 19.0 t C ha^{-1} yr^{-1}. The downslope moldboard tillage moved soil from the upper hillslope and deposited it in concave areas formed by the field boundary. Several authors [*Schumacher et al.* 1999; *Li et al.*, 2001, 2004] have observed substantial losses of SOC due to intensive tillage of agricultural soils. *Schumacher et al.* [1999] concluded that tillage erosion caused soil loss in the shoulder position, while soil loss from water erosion occurred primarily in the mid to lower backslope positions. We observed that SOC accumulation above the field boundary formed by tillage-induced soil redistribution. The decline in SOC was greater when both processes (tillage and water erosion) were combined as compared to either process acting alone, in agreement with *Schumacher et al.* [1999]. The spatial patterns of SOC redistribution over the hillslope suggest that both tillage and water erosion work together to redistribute SOC over the steep cultivated landscapes.

[25] This study showed TSR, total soil redistribution due to combined action of tillage erosion and water erosion, generally resulted in a net SOC loss from the steep cultivated hillslope, although *Van Oost et al.* [2005] reported that tillage-induced soil redistribution has a potential to increase SOC stock on the sloping cultivated landscapes. The net SOC loss induced by TSR was much higher in the last 50 years than before 1954. This accelerated SOC loss is due to intensive tillage operations that result in a removal of SOC in the surface horizon [*Li et al.*, 2006] and a loss of in situ net primary production on steep slopes in China's Loess Plateau [*Liu*, 1985]. In contrast, tillage induced soil redistribution resulted in a significant increase in SOC at the field boundary, even though the net carbon loss over the entire hillslope was significant. The increased SOC (0.020 t C ha^{-1} yr^{-1}) by tillage induced soil redistribution compensated for 8% and 14% of the SOC losses due to

water erosion during 1954–1998 and 1898–1954, respectively. A much higher net SOC loss (0.24 t C ha^{-1} yr^{-1}) from the present study on the cultivated hillslope of the Loess Plateau in the last 45 years than from the cultivated watershed in Ohio (0.114 t C ha^{-1} yr^{-1} for disk till and 0.041 t C ha^{-1} yr^{-1} for chisel till) [*Jacinthe et al.*, 2004] may be explained by the differences in tillage methods, overland flow, slope gradients, and land management practices; however, the trends in soil and carbon being moved are similar for both studies.

[26] Linear correlation between SOC with ^{137}Cs and ^{210}Pb$_{ex}$ was observed in our study, suggesting that SOC in the soil decreased with increased soil erosion, in agreement with previous studies [*Polyakov and Lal*, 2004; *Li et al.*, 2006]. Other studies proposed that SOC content and redistribution were directly related to the quantity of soil eroded [*Slater and Carleton*, 1938; *Kreznor et al.*, 1992; *Bernard and Laverdiere*, 2000; *Pennock and Frick*, 2001], but most of them gave only a qualitative description and few quantifying relationships. The positive relationship was further supported by our previous results [*Li et al.*, 2006] that showed that SOC redistribution, ^{137}Cs and ^{210}Pb$_{ex}$ inventories have the same physical mechanism moving soil and SOC over the cultivated hillslope. This study confirmed the utility of fallout radionuclides as a promising method for tracing the fate of SOC induced by tillage and water erosion covering a timescale of 45 to 100 years. We did not address CO_2 flux during soil redistribution, but we believe that the further study is deserved to be able to quantify the fate of eroded C.

5. Conclusions

[27] The topographical dependency of SOC redistribution induced by tillage and water erosion should be considered when tracing the fate of eroded SOC. Significant increase in SOC amounts at field boundaries of the summit and upper backslopes resulted from tillage-induced soil redistribution. The major losses of SOC from the entire hillslope were attributed to severe water erosion. Soil erosion reduced the SOC pool over the steep cultivated hillslope of the Loess Plateau. Net SOC losses by TSR from the entire hillslope were calculated to 1.65 t C ha^{-1} (0.030 t C ha^{-1} yr^{-1}) during 1898–1954 and 10.65 t C ha^{-1} (0.237 t C ha^{-1} yr^{-1}) during 1954–1998. Tillage-induced soil redistribution could increase SOC and compensate for 8–14% of the SOC losses due to water erosion. The total SOC losses by TSR on entire cultivated area of the Chinese Loess Plateau was estimated to be 0.18 Gt C in the last 45 years and 0.21 Gt C over the last 100 years.

[28] **Acknowledgments.** Financial support for this project was provided by the National Natural Science Foundation of China (grant 40671097), the Talent Project of the Chinese Academy of Agricultural Sciences (CAAS), the International Atomic Energy Agency, Vienna, under research contract 12323, and the Postdoctoral Science Foundation (grant 2004036076). Qingwen Zhang is grateful to China Postdoctoral Science Foundation under grant 2004036076 for her research in CAAS. The authors are grateful to editors and two anonymous reviewers for their constructive comments.

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